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Inclusive inelastic reaction $np \to pX$ at 795 MeV

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The inclusive reaction $np \to pX$, where X includes a pion, has been studied at 795 MeV with measurements of the cross section $d^2\sigma/dp\,d\Omega$. Proton momentum spectra were measured for laboratory angles between 0° and 31°. These angles cover the full forward hemisphere in the center-of-mass system and give, with the use of symmetry assumptions, a value for the total reaction cross section, $\sigma^R = 11.0 \pm 0.8$ mb, exclusive of the $np \to d\pi^0$ reaction. The data are also presented as measurements of the cross section $d^2\sigma/dt\,dM$, where t is the four-momentum transfer squared and M is the invariant missing mass. The results are compared with a model calculation of one-pion exchange that includes ρ and ω exchange. The t dependence is also discussed in terms of a statistical model.

I. INTRODUCTION

Considerable effort is being expended in an attempt to understand the nucleon-nucleon (NN) interaction at 800 MeV in the inelastic channels for pp and np initial states.[1] In the np case where both isospin states, $I=0$ and 1, are present, differential cross sections as a function of angle and momentum for the inelastic reaction $np \to pX$ for energies 740, 882, 1029, and 1180 MeV have been reported by Bizard *et al.*[1] The present work extends the angular range and improves the momentum resolution at 795 MeV, which satisfies the need for data in the large gap between 740 and 882 MeV. It is also of value for a direct comparison with the isospin-related reaction[2] $pp \to nX$ at 805 MeV and 0°. Measurements of the inelastic channel for NN collisions are especially relevant in view of the controversy over the existence of dibaryon resonances[3] alleged to have large inelasticities.[4] Furthermore, specific models can be tested with these data, and in particular the results of a field-theoretic calculation[5] that includes the low-energy NN final-state interaction will be compared with them. The simplest one-pion-exchange (OPE) Feynman diagrams for $np \to pX$ are shown in Fig. 1, where t in the dominant diagram [Fig. 1(a)] is the square of the four-momentum transfer of the virtual pion.

Three results are obtained from this experiment: (1) proton laboratory-momentum spectra for angles up to 31°;

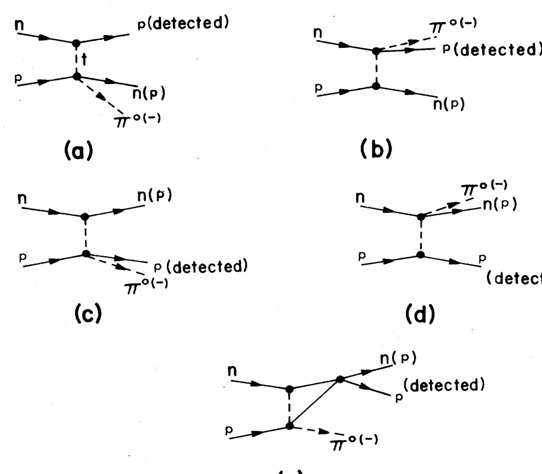

FIG. 1. Principal Feynman graphs for NN single-pion production. (a) The dominant one-pion-exchange (OPE) diagram at small angles. (b) and (c) The detected proton is coming off the πN vertex which includes the $\Delta(1232)$ resonance. (d) The detected proton is associated with the target and the momentum transfer is high. (e) One of several diagrams that show the two nucleons interacting in the final state which leads to an enhancement on the low side of the momentum spectra due to the strong S-wave interaction at low nucleon energies. Dibaryon resonances could lead to enhancement on the high side, as well, through this type of diagram.

(2) cross sections $d^2\sigma/dt\,dM$ as a function of the momentum transfer t for $|t|<0.2$ $(\mathrm{GeV}/c)^2$ and for values of M between 1.10 and 1.24 GeV/c^2; and (3) an extraction of the total pion-production cross section, $np\rightarrow\pi NN$. This last result depends on the two assumptions that isospin invariance holds, and that the πN final-state interactions take place solely through the $I=\frac{3}{2}$ state. The first assumption is necessary because the equality,

$$\sigma(np\rightarrow pp\pi^-)=\sigma(np\rightarrow nn\pi^+)\ ,$$

is needed to calculate the total cross section,

$$\sigma_{\mathrm{tot\ inel}}=\sigma(np\rightarrow nn\pi^+)+\sigma(np\rightarrow pp\pi^-)+\sigma(np\rightarrow np\pi^0)\ ,$$

in terms of the measured quantity,

$$\sigma_m=2\sigma(np\rightarrow pp\pi^-)+\sigma(np\rightarrow np\pi^0)\ .$$

The second assumption ensures the forward-backward symmetry needed to extend the forward center-of-mass (c.m.) measurements to the backward hemisphere. If $I=\frac{1}{2}$ πN interaction amplitudes are not small, interference between these and the $I=\frac{3}{2}$ amplitudes will result in asymmetric distributions centered about 90° in the c.m. system.

II. EXPERIMENTAL METHOD

Experimental details are only sketched briefly here as more complete descriptions appear in reports of companion experiments.[6,7] A nearly monoenergetic neutron beam with resolution ~12 MeV (full width at half maximum) was generated from 800-MeV protons striking a liquid-deuterium (LD_2) target. The neutron beam emerged from a 3.66-m (12-ft) steel collimator at 0° and passed through a liquid-hydrogen (LH_2) target where protons from the reactions $np\rightarrow pn\pi^0$ and $pp\pi^-$ were detected in a spectrometer arranged to pivot about a point directly beneath the LH_2 target.

To ensure that the protons were produced by neutrons near 800 MeV, the relative neutron time of flight (TOF) between the LD_2 and LH_2 targets (~11 m) was determined from the time of the spectrometer fast output measured with respect to every eighth radio-frequency (RF) pulse associated with the structure of the beam. The normal 5-nsec beam-burst separation caused by the RF period of the accelerator was increased to 40 nsec by use of a chopper, which allowed unique energy determination of the incident neutrons for all protons of interest. The incident neutrons were restricted to energies between 760 and 800 MeV through the use of a cut on the TOF with respect to the RF (t_{RF}).

The spectrometer was used to measure the particles' momentum, angle, and TOF over a 4-m flight path. These measurements allowed us to separate protons from pions and deuterons also produced in the LH_2 target. Backgrounds from target walls were removed through use of data taken while the LH_2 flask was empty.

Absolute normalization required a measurement of the product of the integrated neutron intensity N_b and target

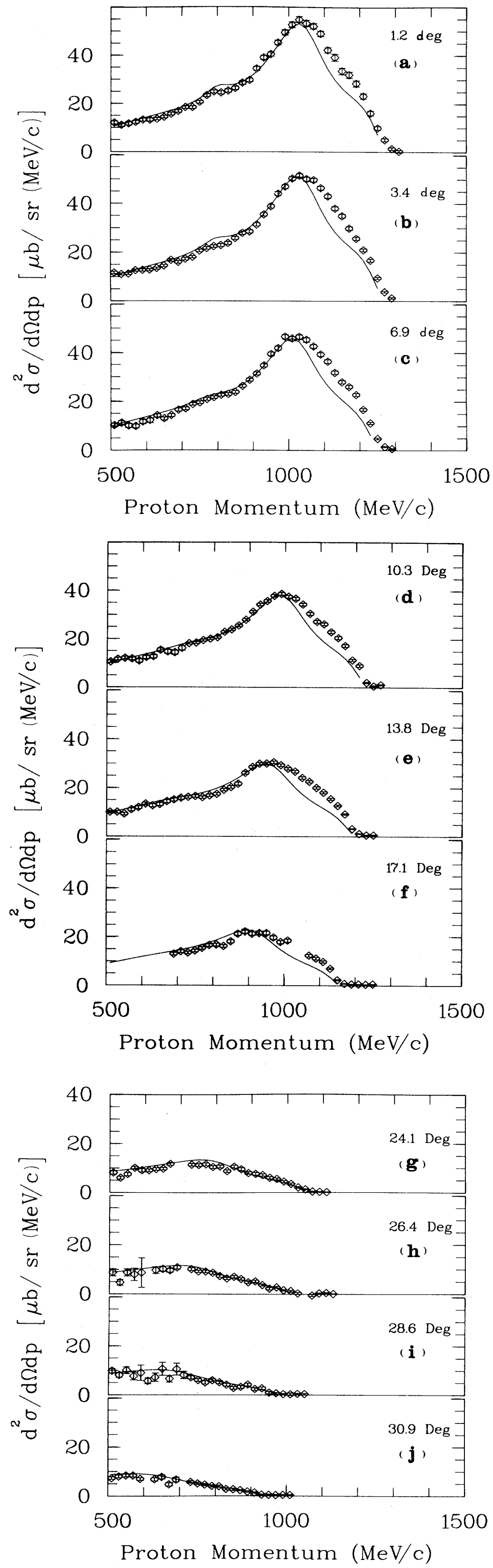

FIG. 2. (a)—(j) The momentum spectra at different angles. The solid lines are theoretical fits to the data (Ref. 5).

areal density N_t. The intensity was monitored with a pair of scintillator telescopes that looked at a thin CH_2 target located just downstream of the collimator in the neutron beam. This monitor was calibrated when the yield of deuterons from the reaction $np \rightarrow d\pi^0$ was measured. When charge independence was invoked the known $pp \rightarrow d\pi^+$ cross section gave a measure of the product $N_b N_t$.

III. RESULTS

The data were converted from yields into cross sections $d^2\sigma/dp\,d\Omega$ for a bin size 0.01 rad$\times$20 MeV/c. The plots in Fig. 2 are for cross sections averaged over larger angle bins, 0.06 rad at small angles and 0.04 at the larger angles. To obtain the cross sections $d^2\sigma/dt\,dM$ in Fig. 3, it was necessary to fill the gaps in the acceptance left by the lack of complete coverage in (θ,p) space by the spectrometer. These gaps were filled with cross sections computed by linear interpolation between θ and p regions where $d^2\sigma/dp\,d\Omega$ had been measured. It was also necessary to remove the effects of discreteness in the values of t computed from the central bin values of θ and p. Therefore the values of t and $d^2\sigma/dt\,dM$ were computed as an average over 50 random selections of momentum between the bin limits. Errors shown in Figs. 2 and 3 are statistical only, and an overall systematic error of about 7% is to be applied whenever absolute cross-section comparisons are made. Interpolation errors are small ($\sim$2%), as only small regions of phase space needed interpolation.

Integrated of $d^2\sigma/d\Omega\,dp$ over the momenta and angles that correspond to the forward hemisphere in the c.m. and over the angular range measured here yields a reaction cross section

$$\sigma^R = 11.0 \pm 0.8 \text{ mb},$$

where R represents the sum of the following reactions

$$np \rightarrow np\pi^0,$$

$$np \rightarrow pp\pi^-,$$

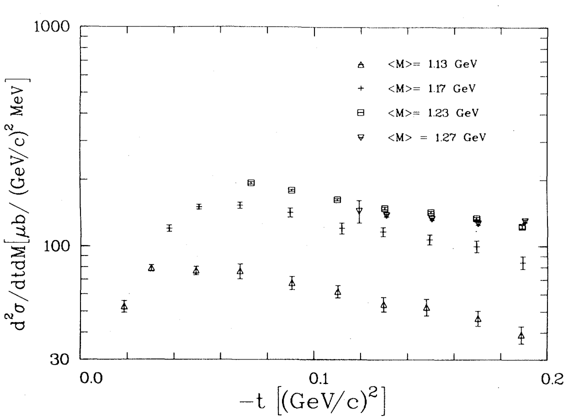

FIG. 3. The cross section as a function of the momentum transfer, t, for different values of average missing mass M: $\triangle$ 1.13 GeV/c^2; + 1.17 GeV/c^2; $\square$ 1.23 GeV/c^2; ∇ 1.27 GeV/c^2.

and

$$np \rightarrow nn\pi^+ .$$

The error includes systematics, whereas double-pion production has been neglected. Furthermore, the value of σ^R depends upon the assumption of isospin invariance along with the dominance of the $I=\frac{3}{2}$ channel in all intermediate states of πN. If the πN interaction occurs exclusively through the $I=\frac{3}{2}$ state, the Rosenfeld partial cross section σ_{01} must be zero to conserve isospin. The subscripts 0 and 1 refer to the inital and final nucleon isospin states, respectively. The results of Thomas *et al.*[8] indicate that $\sigma_{01} < 0.6$ mb, whereas VerWest and Arndt[9] conclude that $\sigma_{01} < 0.2$ mb near 800 MeV. A small value of σ_{01} does not prove the dominance of the $I=\frac{3}{2}$ state, but it lends considerable support to the assumption of this dominance, as nucleons in an initial isospin state, $I=0$, can interact only through $I(\pi N)=\frac{1}{2}$ in an isospin conserving theory. Finally double-pion production at 800 MeV is estimated to be less than 0.1 mb, which is less than the statistical error of the pertinent reaction measurements reported here.

IV. DISCUSSION

Although the measurement of σ^R cannot be used to confirm isospin invariance and $I=\frac{3}{2}$ dominance, as these assumptions were used to arrive at its value, its agreement with the work of VerWest and Arndt[9] (who find $\sigma^R \approx 10.5$ mb) suggests isospin invariance and $I=\frac{3}{2}$ dominance are valid.

Many calculations[10] of single-pion production cross sections in NN collisions exist that invoke the $\Delta(1232)$ resonance as the dominant driving mechanism. In a recent calculation,[5] ρ and ω exchange are incorporated along with π exchange. Off-shell effects are handled with standard form factors at the πNN, $\pi N\Delta$, and corresponding ρ and ω vertices. Some other modifications are made to offset the lack of built-in unitarity,[11] but these do not detract from the model's capacity to give a physical, quantitative account of these reactions. Predictions of the model are shown as solid curves in Fig. 2. Thus VerWest's calculation satisfactorily describes these data over most of the spectra. The approach by Kloet and Silbar[11] has built-in unitarity and, if they were to perform the required integration over the undetected particle phase space, an interesting comparison could be made among their theory, VerWest's, and the data.

Another interesting aspect of these reactions stems from the old idea that a cloud of virtual pions surround the bare nucleon.[12] These pions have a Bose-Einstein statistics momentum distribution corresponding to the characteristic temperature of the pion cloud. The dependence of the cross section $d^2\sigma/dt\,dM$ on momentum transfer is a reflection of this temperature. Lower temperatures correspond to steeper falloff with $-t$ in the small-$|t|$ region, where the diagram in Fig. 1(a) represents the dominant contribution. In Fig. 3, there is a range in the small-$|t|$ region,

$$0.04 < |t| < 0.2 \ (\text{GeV}/c)^2 ,$$

where

$$d^2\sigma/dt\,dM \propto e^{t/b} .$$

This experiment gives $b \cong 0.25$ (GeV/c)^2. At higher energies[12,13] ($6.6 < P_{\rm inc} < 24$ GeV/c), one finds $b \cong 0.09$ (GeV/c)^2. This steeper momentum dependence (lower temperature) at higher energies could be a manifestation of the increased peripheral nature of the reaction, which would mean that the outer regions of the pion cloud are probed more at the higher energies. We would expect to find, for pions in a potential well, the outer region of the pion cloud to be at a lower temperature than the more interior section. The peripheral nature of the pion production process is reduced at lower energies because of kinematics. For constant values of t the virtual three-momentum must be higher at lower incident energies. A larger value of this three-momentum (larger kinetic energy) implies that the pion probably comes from a region where the equivalent potential well is deeper and therefore more interior to the nucleon. In the statistical model of Galloway *et al.*,[12] the high-energy pion production leads to a temperature around 80 MeV, whereas the present 800-MeV results give ~ 150 MeV, very close to Hagedorn's[14] maximum temperature for hadronic matter.

An alternative explanation for the steeper $-t$ dependence at higher energies is given by Reggeization of the pion propagator, but the Regge-exchange model does not predict the pronounced dip for $|t| < 0.015$ (GeV/c)^2 in the 15 GeV/c πp results of Bulos *et al.*[15] The statistical model[12] with an appropriate effective-pion-mass value for the virtual or bound pions ($\simeq 0.1$ GeV) predicts this dip. The data in the present experiment also indicate the presence of this dip, although not in as pronounced a manner as does Bulos *et al.*[15] The onset of the dip in this experiment is at $|t| \simeq 0.05$ (GeV/c)^2, which is far too high to be accommodated by a Regge-exchange mechanism alone.

It is instructive to compare in detail the $pp \to nX$ spectra[2] with the present results for $np \to pX$ at 0°. In Fig. 4, the ratio of these cross sections is shown over the region of momentum covered by these experiments. Reference 2 points out that in the simplest approximation this ratio should be ≈ 3. Clearly this simple approximation does not apply, especially for momenta away from 1000 MeV/c where the value of M is 1.23 GeV/c^2. At ~ 1000 MeV/c, where the ratio peaks, it falls short of being 3, but its value of ~ 2.2 indicates that the approximation approaches validity where one would expect. From an isospin-amplitude analysis, in the extreme case where the np amplitudes for Δ^0 and Δ^+ production add constructively and the pp amplitudes for Δ^{++} and Δ^+ add destructively, the ratio $\sigma(pp)/\sigma(np)$ can be as small as ~ 0.44, with no contributions from $N\pi$ states with $I = \frac{1}{2}$. The ratios plotted in Fig. 4 are above this value except for the last point.

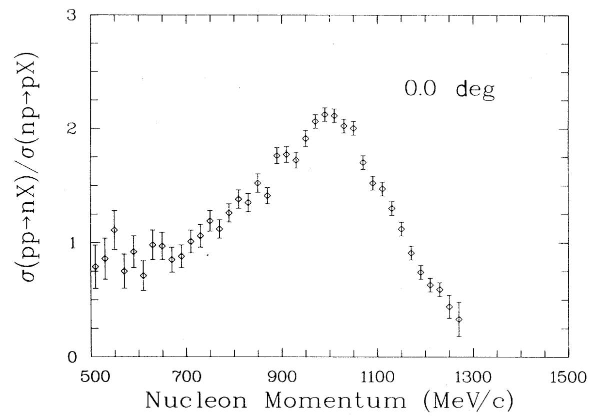

FIG. 4. The ratio of inclusive differential cross sections for pp and np pion production with the nucleon detected at or near 0°, as a function of the detected nucleon momentum.

V. CONCLUSIONS

The level of agreement of the field-theoretic calculation of VerWest[5] with these data is impressive, especially in view of the few free parameters in the theory. This approach also leads to reasonable fits to most of the single-pion-production data in this energy region.[1,2,8] However, the measured cross sections for angles $\leq 17°$ disagree with VerWest's predictions significantly at the high-momentum end of the spectra in Fig. 2. The NN invariant mass for this region lies between 2.0 and 2.1 GeV/c^2, and should there be any NN resonance (dibaryons) nearby it would not be surprising for VerWest's calculations to disagree at this end of the spectra. However, this part corresponds to the small-$|t|$ region and even in the absence of dibaryons the theory may be unable to reproduce the data in this region either because unitarity is neglected or because standard form factors are used where the statistical model calls for a momentum distribution derived from Bose-Einstein statistics.

The statistical model fails in that the high-energy results imply a much different equivalent temperature than that given by the 800-MeV results obtained here. Although this difference is plausible according to arguments given in Sec. IV, the statistical model still lacks quantitative content and does not explain these phenomena from fundamental principles. No one model appears to give a completely satisfactory description of single-pion production in NN collisions. The validity of the Kloet-Silbar approach in these inclusive types of experiments[2,9] has yet to be verified.

In conclusion, these data are not thoroughly understood within the present framework of accepted principles or of any one model. With refinements and extensions of VerWest's model, we expect that the data can be reproduced better. The development of quark models which introduce a six-quark bag component to the two-nucleon state[16] may also add to our understanding of single-pion production in NN collisions.

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